Structure, Energetics and Variability of the Non-Linear Internal Wave Climate over the New Jersey Shelf

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LONG-TERM GOALS

I seek to obtain a more complete and fundamental understanding of the hierarchy of processes which transfer energy and momentum from large scales, feed the internal wavefield, and ultimately dissipate through turbulence. This cascade significantly impacts the acoustic, optical, and biogeochemical properties of the water column. Non-Linear Internal Waves (NLIWs) represent one such pathway.

OBJECTIVES

Non-Linear Internal Wave (NLIW) packets are ubiquitous features of the coastal ocean, producing significant changes to its acoustics, optics and biogeochemistry, and influencing its dynamics. While they arrive like clockwork in some regions like the South China Sea, they occur with a high degree of variability on most continental shelves like the New Jersey shelf – site of the SW06 experiment. And even in regions where they form at regular intervals, their amplitudes can vary dramatically from packet to packet, and there are strong seasonal changes.

Through this project, I seek to:

- describe the 3D structure, energy and timing of the ~100 NLIW packets that propagated through the SW06 mooring array;
- elucidate the process by which a nearly-linear internal tide steepens and forms NLIWs;
- understand what sets the conversion efficiency between barotropic tide, baroclinic tide, and NLIW packets;
- determine the external factors (seasonal/mesoscale/tidal) that control NLIW energetics and variability in the coastal environment; and
- quantify the sensitivity of indirect measures (SAR imagery, glider dynamics, bottom pressure) to detect NLIW amplitudes/energy/timing.

Together, these improve our ability to detect, predict and quantify the effects of NLIWs in an arbitrary coastal environment.

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14. ABSTRACT
Non-Linear Internal Wave (NLIW) packets are ubiquitous features of the coastal ocean, producing significant changes to its acoustics, optics and biogeochemistry, and influencing its dynamics. While they arrive like clockwork in some regions like the South China Sea, they occur with a high degree of variability on most continental shelves like the New Jersey shelf ? site of the SW06 experiment. And even in regions where they form at regular intervals, their amplitudes can vary dramatically from packet to packet, and there are strong seasonal changes.

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APPROACH

Three water-column moorings and four bottom landers were deployed to capture the full water column variability of density (sound speed), velocity and bottom pressure. Combined with the other SW06 resources, the 3D wave structure, propagation direction, baroclinic energy density and energy flux is determined. Data integration with wave-tracking experiments is used to confirm moored energy/flux estimates. Divergences of energy flux are used to assess generation location and conversion efficiencies, and phasing of baroclinic signals (and their relationship to the barotropic tide) elucidate mechanisms. Model-data comparisons are used to aid interpretation.

WORK COMPLETED

A full census of NLIW timing, structure, propagation direction, and wave energetics at all SW06 ADCP moorings has been completed (SW29, SW30, SW32, SW34, SW37, SW38, SW39, SW41, SW42 & SW43). This forms a wave inventory database used for higher-order calculations. This database, CTD-ADCP mooring data (w/ Duda) and ADCP/P-pod bottom lander data (w/ Moum) are available for use by SW06 collaborators.

RESULTS

Analysis of NLIW timing, 3D structure and energy at SW06 reveals that this site is highly complex – typical of coastal internal wave climates. Not only was the amplitude, timing and propagation direction highly variable, but the NLIW energy was found to be unrelated (or inversely related?) to the strength of the shelfbreak barotropic tide (Figure 1). Instead, NLIW energy levels are found to be highly correlated to the strength of the internal tide. The complex NLIW climate at SW06 site dramatically contrasts the regularity of waves and timing in the South China Sea. This contrast may simply be a reflection of the relative complexities of the internal tide in these two regions.

So our original question *"What sets the intensity of NLIWs on the continental shelf?"* has evolved into… *"What sets the structure, intensity and direction of the internal wave energy flux at the shelfbreak?"*

While topography, seasonal stratification, and barotropic forcing are certainly important, these do not explain the low-frequency trends in baroclinic energy, nor do they account for the packet-to-packet variability in NLIW shape, amplitude or timing. Subtle changes in the location of shelfbreak fronts, sub-tidal currents, near-inertial variability, and other factors must play a role in setting the strength of the internal tide, its nonlinear steepening, and subsequent propagation of NLIWs.

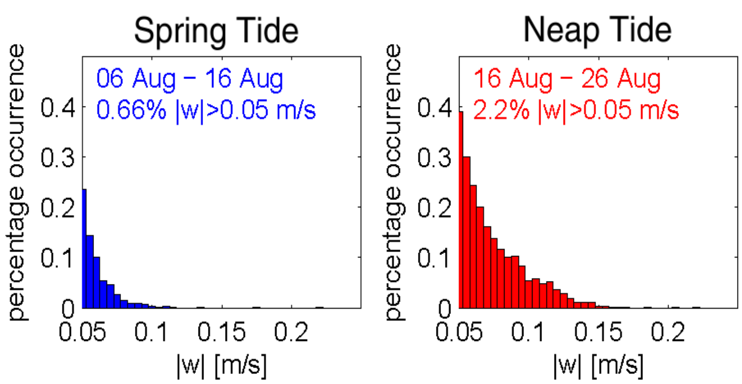


Figure 1: Distribution of vertical velocity at SW37 (70-m isobath) during spring (left) and neap (right) August 2006 tides. The average vertical velocity and energy of NLIW packets during the August 2006 spring tide was about 25% of that during the following neap tide. In contrast, barotropic velocities during spring tides were almost a factor of 2 stronger than the neap.

The following outlines progress to date in 5 major areas:

1) NLIW Pressure p_w

In collaboration with Jim Moum, bottom pressure was directly measured on three bottom landers. Our analysis (Moum and Nash 2008) confirms that (1) we are correctly computing the wave-induced internal pressure $p_w=p_{surf}+p_{hyd}+p_{nhyd}$ and (2) wave amplitude, timing and sign (depression vs. elevation) can be measured from bottom pressure P-pods. This measurement provides a means for detecting and quantifying waves both waves of depression and elevation, which is significant, as the latter have no detectable sea surface signature.

2) NLIW Energy and Energy Flux

NLIW energy ($E=APE+KE$) and energy flux ($\boldsymbol{F_E} = < \boldsymbol{u_w}\, p_w > + \boldsymbol{u_w}\, E$) have been computed for all waves during the experiment at all ADCP moorings; a summary from five inshore moorings is shown in figure 2. The nonlinear contribution to the energy flux ($\boldsymbol{u_w}\, E$) is found to be appreciable for most waves (usually >25% of $\boldsymbol{F_E}$), and that on average the flux is represented by $\boldsymbol{F_E} \approx \boldsymbol{c}\, E$, confirming our findings based on waves of elevation (Moum et al 2007). Moreover, for the first wave in each packet, energy is found to be equipartitioned ($KE \approx APE$) so that $\boldsymbol{F_E} \approx 2\, \boldsymbol{c}\, KE$, (Shroyer et al 2008). This result provides a simplified means of estimating NLIW energy and flux, if the result is indeed as universal as it appears to be.

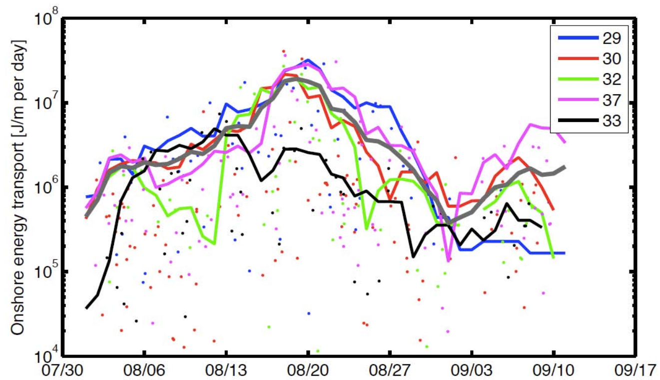
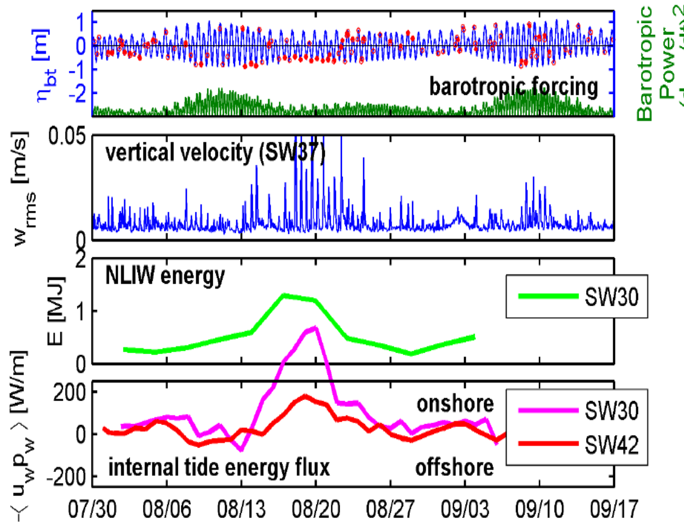


Figure 2: Time-series showing onshore transport of energy by NLIWs at 5 inshore moorings. Dots represent the energy transport within individual wave packets; solid lines represent 24-h averages (mean of the 5 moorings in grey). The peak energy near Aug 20 occurs during neap tides and is a factor of ten greater than that during spring tides. Mooring SW33, located 25 km N of the central cluster, recorded much lower NLIW energies and exhibits a different temporal pattern.

3) NLIW Temporal and Spatial Variability

NLIW amplitudes during SW06 showed strong along-shelf variability, with factor-of-ten differences over just 15 km separation (Figure 2; compare SW32 and SW33.) Moreover, NLIW energies were highly variable on synoptic timescales (Figure 2) and poorly correlated with the barotropic tide (Figure 3). NLIW variability is instead explained by the variability in the internal tide, which shows a similar temporal structure. This confirms that NLIW intensity is controlled by the strength of the internal tide. A more complete understanding of the mechanisms that set the strength of the internal tide (both spatial and temporal variability) is necessary for prediction of the NLIW generation.

Figure 3: Summary of NLIW temporal variability. Forcing by the barotropic tide (elevation & power; top row) is poorly correlated with NLIW vertical velocity at SW37, the 70-m isobath (2nd row). Red dots in upper panel represent wave arrival times at SW37. The resultant NLIW energy (3rd row) is found to covary with the internal tide energy flux, both inshore and at the shelfbreak (bottom row).



Wave arrival times were moderately phase-locked to the barotropic tide only during 8/16-8/23 (red dots in upper panel, figure 3) – a period when NLIW packets arrived on the leading edge of the steepened internal tide (figure 4). But even during this period, there is no one-to-one correspondence between the strength of internal tide pulses at the shelf break (upper panel) and the amplitude of NLIW packets that arrive at the 80-m isobath 7 hours later (Moum and Nash, 2008 – figure 2). Influences from the mesoscale stratification & velocity, deviations in internal tide phasing or direction, and/or interactions with other waves must be responsible for this complexity.

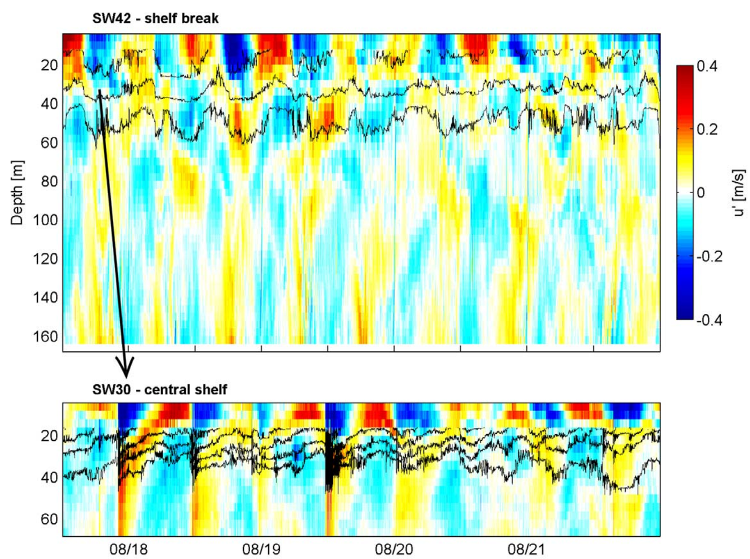


Figure 4: Depth-time plot of velocity (color) and density (contours) at the shelfbreak (top) and 70-m isobath (bottom). NLIWs appear inshore on the leading edge of the steepened internal tide.

4) Internal Tide Structure & Generation

SW06 shelfbreak moorings reveal strong gradients in the internal tide energy flux, computed following Nash et al (2005). During most time periods, the shelf break is one source of the internal tide (Baines 1982), with energy radiating both onshore towards the shelf and offshore over the slope, roughly along tidal characteristics (Figure 5). However, during the 16-26 Aug period of strong NLIW activity, the internal tide source appears to have shifted offshore to at least the 500-m isobath. The source of this baroclinic energy and the reason for its intensification are not currently known. However, such variability is common of many continental shelves – from the US east and west coasts (Nash et al 2004, Lerczak et al 2003, Nash et al 2007) to the SCS (Duda and Rainville, 2007).

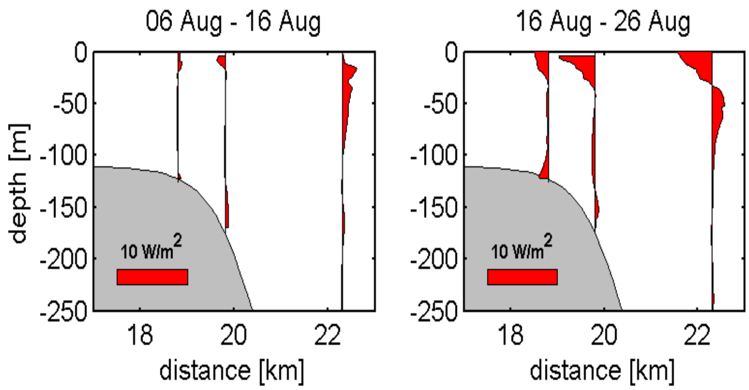


Figure 5: Energy flux profiles near the shelfbreak during periods of weak (left) and strong (right) NLIW activity. A 5 W/m^2 onshore internal tide occurs at all stations during strong NLIW activity.

5) NLIW/ Internal Tide covariance and conversion:

Using our census of NLIW events and energetics, we are able to assess the conversion efficiencies from the quasi-linear internal tide to NLIWs, and by combining these with measured dissipation estimates (both direct, from Moum's wave tracking, and indirect, from the decay of NLIW energy fluxes), will provide a complete description of the energetics through the lifetime of a NLIW packet.

IMPACT/APPLICATION

These analyses provide the physical understanding of mechanisms so NLIW occurrence, energetics, and propagation characteristics can be predicted. This will lead to a general understanding of processes to aid NLIW prediction elsewhere.

RELATED PROJECTS

These observations and analysis are part of a coordinated effort to define the structure, energetics and timing of the signals that emerge from the interaction of the stratification with the shelf break for other DRI participants. In addition, a combination of long and short-term programs on the New Jersey shelf (initiated by personnel at Rutgers University, the CoOP-sponsored LATTE program, LEAR and AWACS) includes additional moorings, gliders, and surface velocity from long-range (100 nm) CODAR coverage. These projects are highly synergistic and will be used to study a wide variety of physical, biological and acoustic properties of the region.

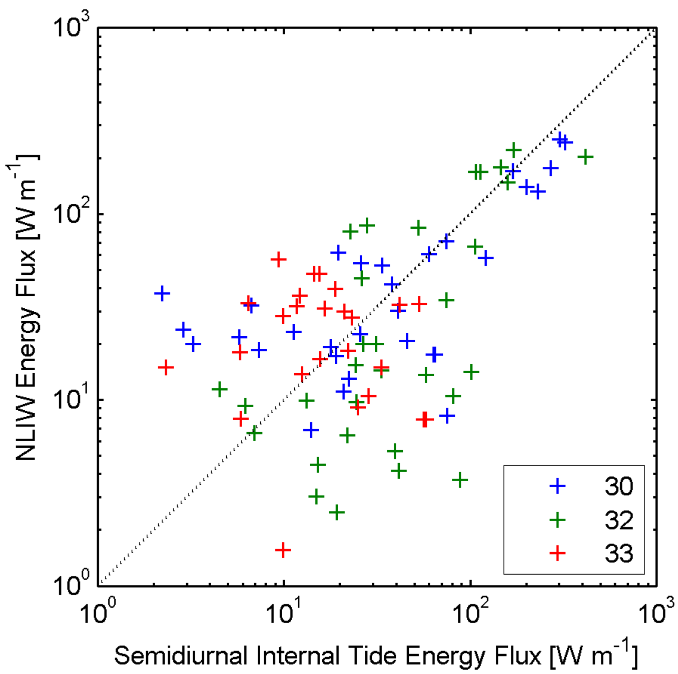


Figure 6: At the central cluster (SW30 & 32), the NLIW energy flux carries most of the energy associated with the internal tide. At the northern site (SW33), the relationship between NLIW and internal tide energetics is less clear.

Despite dramatic differences in NLIW climate at the SCS and NJ shelf sites, there are important common threads in these two

NLIWI DRI projects. Most significant, NLIWs seem to first appear at the internal tide surface reflection at both SCS and SW06 sites (albeit with dramatically different signal strengths). Differences in NLIW regularity and three dimensionality at each site may arise solely from the contrasting complexities in the internal tide: SW06→ complicated, SCS→simple. If this is indeed the case, accurate prediction of the linear, internal tide may be sufficient to predict NLIW energy levels. A common connection between the two NLIWI experiments may be the importance of mesoscale/seasonal changes to NLIW generation and variability. We expect to elucidate these connections through participation in the Internal Waves in Straits Experiment (IWISE).

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